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Thermally Induced Groundwater Flow Resulting from an Underground Nuclear Test

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Abstract

We examine the transient residual thermal signal resulting from an underground nuclear test (buried below the water table) and its potential to affect local groundwater flow and radionuclide migration in a saturated, fractured, volcanic aquifer system. Thermal profiles measured in a drillback hole between 154 days and 6.5 years after the test have been used to calibrate a non-isothermal model of fluid flow. In this process, we have estimated the magnitude and relative changes in permeability, porosity and fracture density between different portions of the disturbed and undisturbed geologic medium surrounding the test location. The relative impacts of buoyancy forces (arising from the thermal residual of the test and the background geothermal gradient) and horizontal pressure gradients on the post-test flow system are better understood. A transient particle/streamline model of contaminant transport is used to visualize streamlines and streaklines of the flow field and to examine the migration of non-reactive radionuclides. Sensitivity analyses are performed to understand the effects of local and sub-regional geologic features, and the effects of fractured zones on the movement of groundwater and thermal energy. Conclusions regarding the overall effect of the thermal regime on the residence times and fluxes of radionuclides out of the system are drawn, and implications for more complicated, reactive contaminant transport are discussed.

Introduction

There is increasing concern about environmental risks posed by radionuclides produced by underground nuclear tests [USDOE, 1997; IAEA, 1998]. These risks are dependent, in large part, on the physical and chemical mechanisms that control the extent to which radionuclides are introduced and transported in groundwater. In this paper, we review a series of thermally driven flow simulations designed to evaluate the impacts of residual high temperatures on groundwater movement at the Cheshire nuclear test at the Nevada Test Site (NTS). The simulations represent an significant step in understanding (i) the nature of buoyancy driven flows that may develop in the vicinity of a nuclear test and their potential for moving radionuclides vertically out of the blast cavity; (ii) the importance of lasting high temperatures in accelerating the release of radionuclides from melt glass debris produced with the test, and (iii) the time required for the high temperatures and disturbed flow fields to relax or decay to ambient (background) levels. Such results will ultimately be used in conjunction with reactive transport simulations [Tompson et al., 1999] to better understand the complex mechanisms involved in radionuclide release out of such systems and design data acquisition strategies for future validation and characterization purposes.

Nuclear Test Effects and Phenomenology

The detonation of an underground nuclear device releases an immense amount of energy that vaporizes the geologic and device-related materials in a local region surrounding the testing point [Borg et al., 1976; Germain and Kahn, 1968]. This produces a cavity into which overriding formation materials eventually collapse, creating a vertical "rubble" chimney that may extend to the surface. Immediately after the explosion, compressive shock waves will fracture or alter the formation beyond the cavity wall. Rebounding compressive stresses serve to retain most radionuclides near cavity region. For tests conducted beneath the water table, groundwater will also be vaporized near the explosion point. As temperatures cool and gas pressures dissipate, components of the cavity gasses will begin to condense and accumulate into a melt glass puddle at the bottom of the cavity. The melt glass debris largely retains the chemical composition of the host rock, but will incorporate the heavier radionuclides produced by the test [Smith, 1995]. Lighter radionuclides will later condense along the collapsed rubble surfaces and cavity walls above the melt zone. Eventually, groundwater will refill the cavity region. To the extent that groundwater flows through the region, it will provide a mechanism for the transport of radionuclides (that are either leached from the melt glass or reside in the cavity rubble) away from the test.

Background on the Cheshire Nuclear Test

The Cheshire test was conducted on February 14, 1976, on Pahute Mesa at NTS (Area 20 in Figure 1). The working point of the test was located 1,167 meters below the ground surface and 542 meters below the water table, while its announced yield range was 200–500 kilotons [USDOE, 1994]. The test was located in relatively low permeability rhyolitic lava, with more permeable (i.e. high fracture density) zones located in the upper portions of the saturated zone [Blankennagel and Weir, 1973; Sawyer et al. 1999].

Unclassified calculations based on the upper value of the announced yield range were used to estimate a cavity radius of 80 meters and a volume of melt glass equal to 240,000 cubic meters. Based upon post-test data, the collapsed chimney was determined to extend above the water table [Jorgensen, 1987], but not as far as the ground surface, as no crater was observed at surface ground zero [Carlson and Wagoner, 1991]. Figure 2 depicts an overview of the geology and disturbed zones of the Cheshire test.

Radionuclide migration away from this test has been the subject of considerable study [Sawyer et al. 1999]. Tritium has been observed in groundwater in the permeable zones above the cavity, which suggests vertical flow and migration have occurred after the test. Although the regional hydraulic gradient is predominantly horizontal (between 0.007 and 0.01 [m/m] to the southwest), a small vertical component has been measured and cited as a possible mechanism to drive flow up through the chimney region [Brikowski, 1991]. However, this gradient was measured over a large distance and may not be representative of local conditions. In addition, there is only very limited data regarding hydraulic and other physical properties of the disturbed (cavity, chimney, melt glass) and undisturbed regions around the test. In this paper, we explore an alternative hypothesis in which the residual heat of the test is considered to generate buoyancy-driven vertical flow in the chimney region.

Cheshire Thermal Data

Following the Cheshire test, a series of drillback holes were constructed for diagnostic information and were later used for water sampling and temperature profile measurements. One drillback hole of interest (labeled U20n-PS1DD) was located 381 meters away from the main emplacement hole (U20n). This borehole was drilled roughly vertically until a depth of 335 meters and then in an angled, curvilinear sense to intersect the chimney, cavity, and melt glass of the Cheshire test (Figure 2). Several thermal profiles were taken in this hole at different times after the test. Three of these (labeled runs two, three and four) provide useful, continuous measurements of temperature at 154, 201 and 2,356 days after the test. These logs show that significant thermal profiles existed across the cavity and chimney horizon as long as 6.5 years after the test. At all times, the highest temperatures were generally confined to the melt glass (150 °C at 154 days), with cooler, yet above ambient, temperatures in the cavity region (50 °C at 154 days).

Ambient temperature profiles were measured in the device emplacement hole (U20n) before the test. Logs in this borehole (specifically, log U20n Run 10) indicated that a vertical geothermal gradient of 0.007 [°C/m] was present in the system. The temperatures and gradient measured in the emplacement hole agree with the temperatures and gradient measured in the uppermost segments of the post-test logs, which were located in the undisturbed host rock, some distance from the cavity-chimney region.

2D Model and Calibration

A simple two-dimensional (radially-symmetric) model of thermally-driven fluid flow was developed to study the movement of water and dissipation of heat in the immediate region surrounding the Cheshire test. Given the limited amount of thermal and hydraulic property information related to the host rock and disturbed units, the temperature log data was used to calibrate our estimates of material properties.

The model was constructed using the NUFT (Non-isothermal, Unsaturated-saturated Flow and Transport) model [Nitao, 1993; Lee et al., 1993]. The modeling domain encompassed the cavity, chimney, melt glass and undisturbed zones in the near field vicinity of the Cheshire test and extended from below the melt glass up to the water table. Initial estimates of thermal and hydraulic properties were made for these four units, and a calibration process was begun. The ambient (vertical) geothermal gradient was included in the model, but the regional hydraulic gradient was not. The two high permeability units shown in Figure 2 were also not included in this model. The melt glass region was initialized to a temperature slightly above the value measured at 154 days. The initial cavity and chimney temperatures were also estimated at slightly above ambient temperature. These initial temperatures for the melt glass, cavity and chimney were adjusted in the calibration process. The model was started at a time prior to the first thermal profile (154 days) to allow the initial development of convective flow. The thermal profiles from PS1DD logs were mapped onto the model domain and were used as calibration targets for the computer model.

Of the several calibration runs simulated, “Run V” most accurately matched the three measured thermal profiles. The calibration sequence suggested that cavity and chimney permeabilities are larger that the of the host rock, while the melt glass permeability is, on average, much lower. Figure 3 shows the final temperature and material property values. Figure 4 compares the model results with the measured thermal profiles. Additional runs were conducted to estimate the persistence of the thermal signal beyond the last measurement time of

2,356 days. These runs showed the thermal signal to be present well after 10 years, but significantly diminished by 100 years.

3D Model

Using calibrated values from the 2D study, a fully three-dimensional model of heat and water flow in the cavity, chimney and surrounding undisturbed rhyolite was constructed. This model included the all the features of the two-dimensional model (geothermal gradient and calibrated property values for the disturbed units) plus the regional hydraulic gradient, and a single horizontal, high permeability layer above the cavity, mentioned previously and inferred from borehole data [Sawyer et al., 1999]. This high permeability unit was assumed to be contiguous across the domain, and would potentially allow for water and radionuclides to flow upward through the cavity and exit horizontally out of the domain. The configuration of the three-dimensional model domain is shown in Figure 5. The sensitivity of the system to these features was studied in subsequent simulations.

Figure 6 shows the results of one such run, displaying the three-dimensional temperature profile 201 days after the test. The calibrated property values obtained in the 2D model were unaffected by the new features of the 3D model. Figure 6 also shows a series of instantaneous flow streamlines launched from the bottom of the domain, as derived from the flow model at 201 days. Flow is entering the domain along the entire upgradient and bottom faces of the domain, but for visualization purposes, the streamlines shown only denote flow paths originating from the bottom of the domain. Figure 7 shows the geologic units used in the 3D model, overlaid by a series of streaklines launched from the center of the cavity. The streaklines represent the transient motion of tagged parcels of water through the domain over the course of the simulation. They are color coded to represent time of travel and may be used to estimate the residence time of a conservative (i.e. non-sorbing, non-reactive) tracer in the cavity-chimney system. Circulation cells that develop early in the simulation are clearly visible.

Figure 8 shows the results of a steady-state simulation that incorporates only the ambient geothermal and regional hydraulic gradients, without the test-induced thermal signal. The temperature field is shown (with a different color scale than Figure 6) with streamlines colored to denote travel time. At steady-state, the pathlines depicted by streamlines are identical to streaklines, so the travel times indicated by the streamlines in this figure may be compared to the travel times indicated in Figure 7. It should be noted that the streamlines shown in this figure only denote flow originating from the bottom of the domain.

Conclusions and Future Goals

In an effort to increase our understanding of radionuclide migration after an underground nuclear test, we have presented thermal data and a sequence of calibrated groundwater and heat flow simulations near the Cheshire underground test. The results have been extremely useful in calibrating hydraulic properties of the disturbed and undisturbed media surrounding the test. The measured temperature profiles and calibrated computer simulations support thermally-driven upward groundwater flow in the vicinity of the Cheshire cavity-chimney system.

Model results indicate that the high temperatures associated with the test will persist on the order of tens of years, and may facilitate conservative transport from the cavity region to the upper chimney region in time scales of 10-20 years (Figure 7). This may be contrasted with conservative transport under ambient conditions (Figure 8), which may occur over time scales of 100 or more years. A high permeability zone located in the upper saturated zone, connected with the cavity-chimney system allows for accelerated conservative transport away from the vicinity of the test location.

Future work will use geostatistical techniques to more accurately and realistically account for the spatial variability of the high permeability geologic layer shown in Figure 5, representing this layer as three distinct zones of high fracture density. Because most radionuclides of interest at NTS do not act as conservative tracers, more substantial models of reactive transport will be required to address the elution of these constituents out of the melt glass and cavity system [Tompson et al. 1999]. This will require a clear understanding of the role that post test thermal signals play in the movement of heat and water in the vicinity of the Cheshire cavity-chimney region as shown here.

Acknowledgements

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Figures

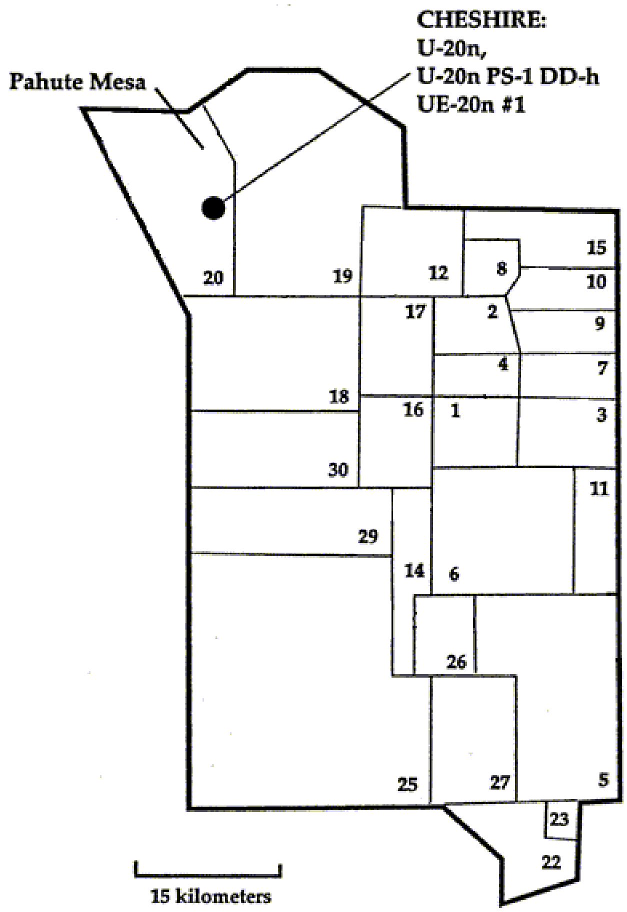

Figure 1. Map of the Nevada Test Site, showing Pahute Mesa, Area 20 and the Cheshire test (U-20n).

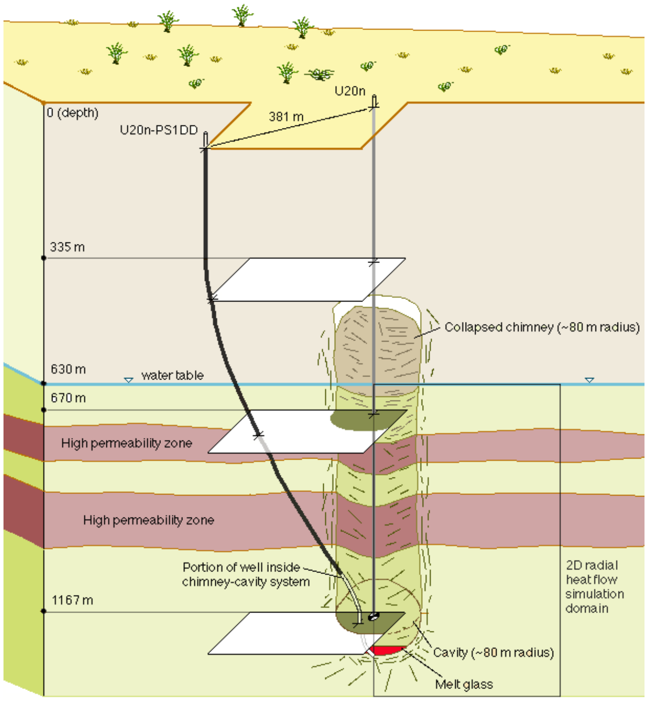

Figure 2. Configuration of the post-test disturbed zone (cavity, chimney and melt glass) with the location of the PS1DD drillback hole, water table, and approximate geologic units. Note the delineation of the 2D modeling domain.

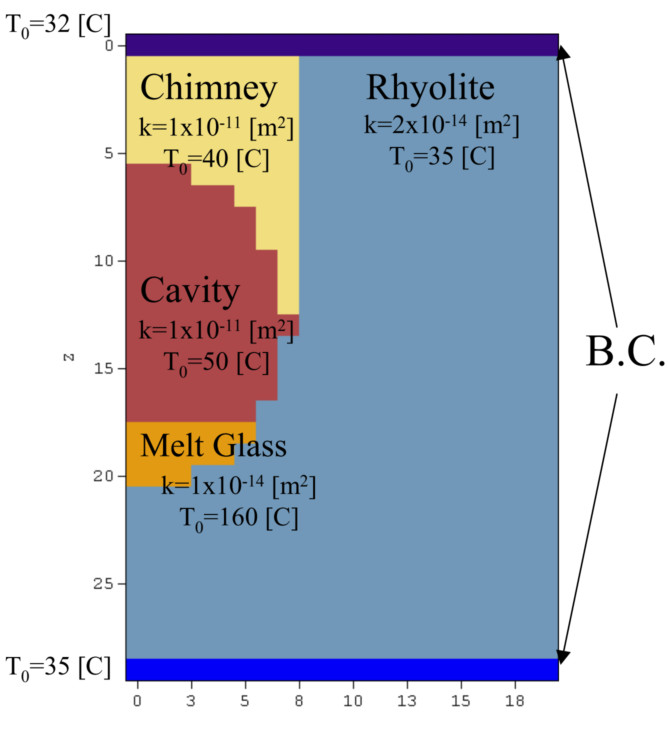

Figure 3. Calibrated 2D radial model domain. The different units, initial temperatures, permeabilities, and boundary conditions are noted on the figure.

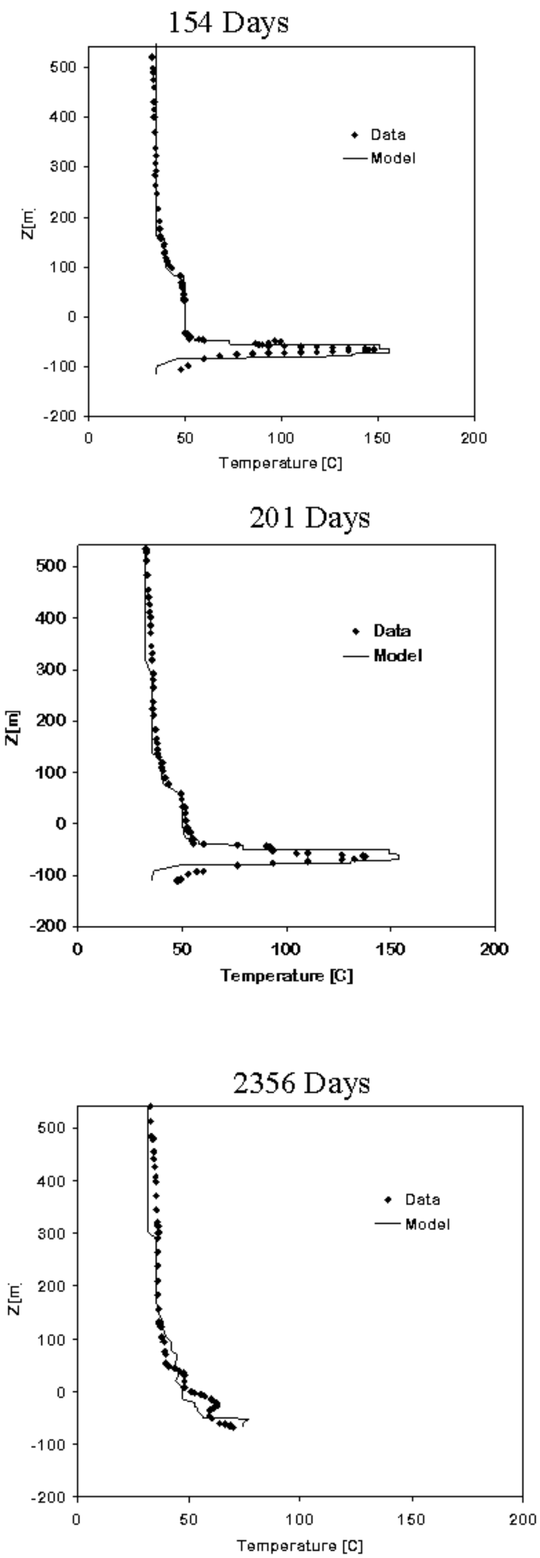

Figure 4. Comparison between measured temperature profiles (symbols) and predicted model temperatures (solid lines) for the 2D model Run V.

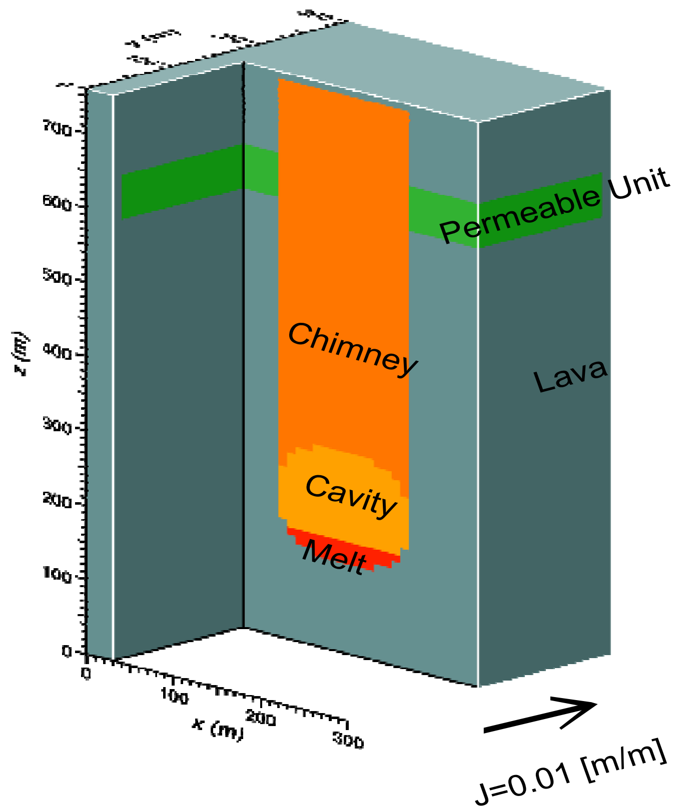

Figure 5. Configuration of the 3D model domain.

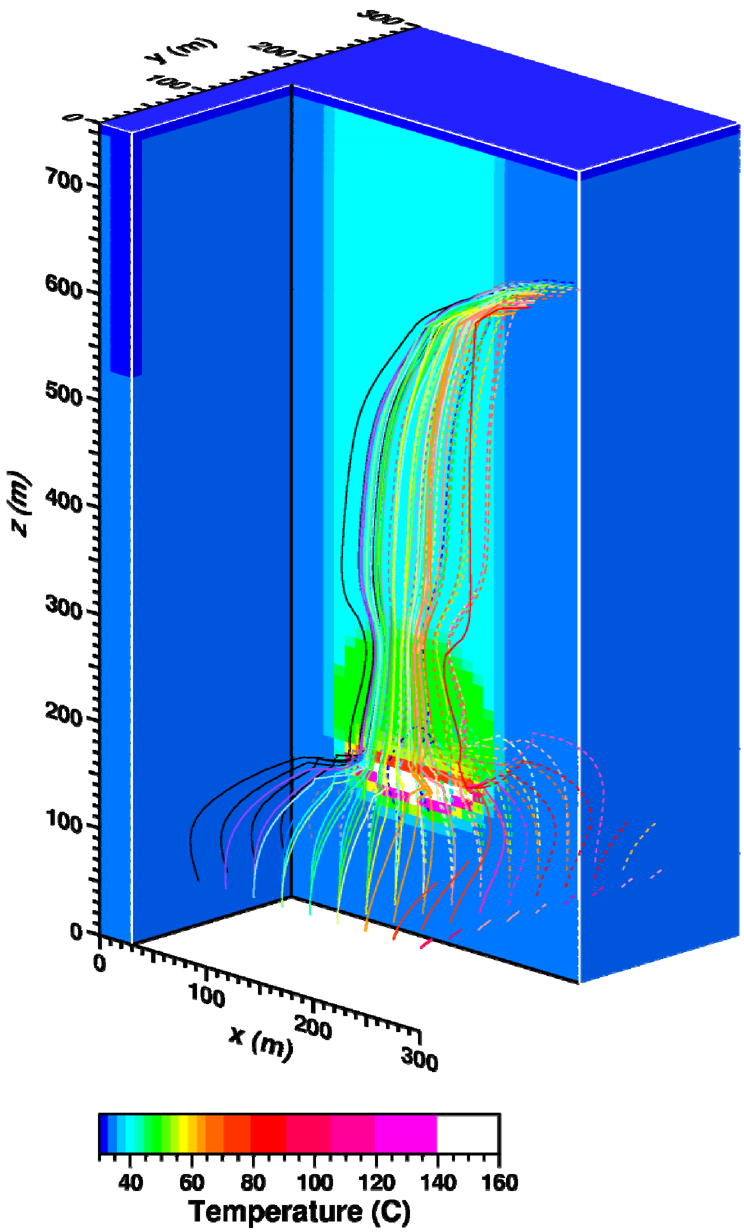

Figure 6. Thermal profile and instantaneous streamlines launched from the bottom of the domain for 201 days post test. This simulation includes post-test, geothermal and hydraulic gradients.

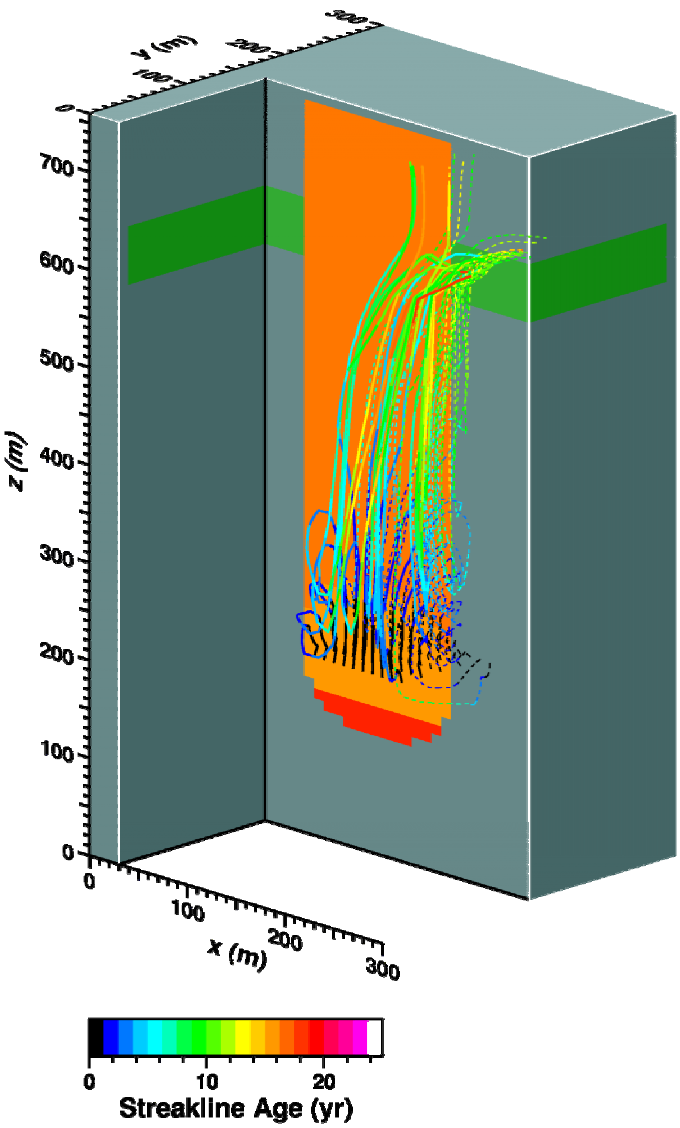

Figure 7. Model domain and transient streaklines launched from a plane intesecting the working point. The color on the streaklines denote the time of travel. This simulation includes post-test, geothermal and hydraulic gradients.

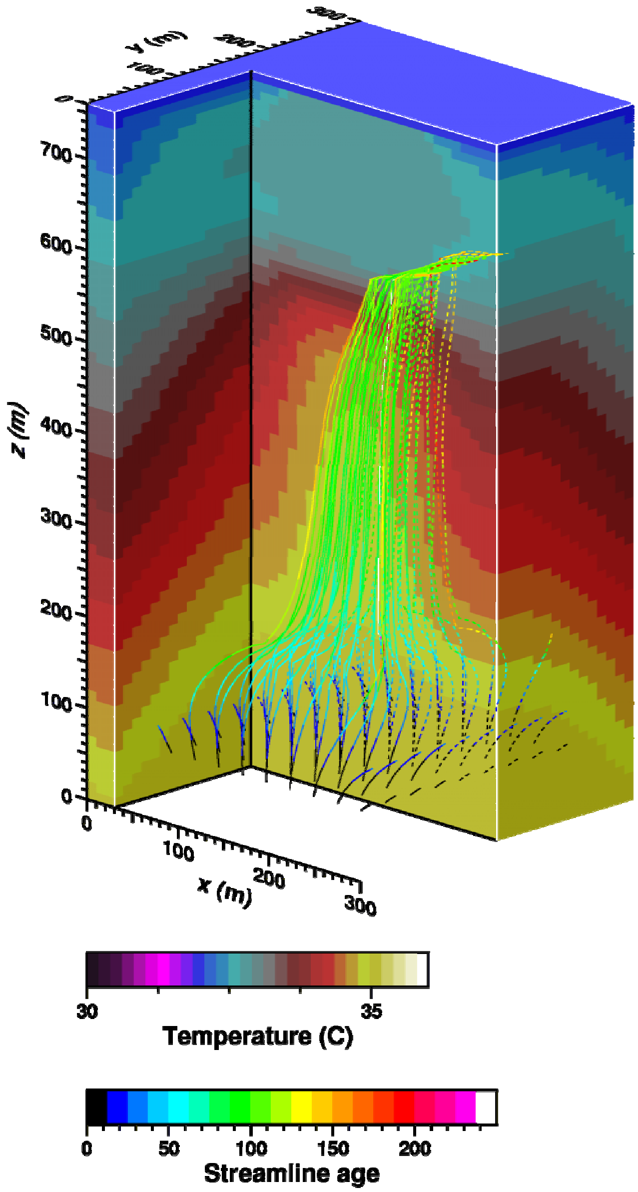

Figure 8. Thermal profile and streamlines for a steady-state (geothermal and hydraulic gradients only) simulation. Note the color of the streamline denotes time of travel, and the different temperature scale from Figure 6. The streamlines shown in this figure are launched only from the bottom of the domain.